

Parameter Space of General Gauge Mediation

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We study a subspace of General Gauge Mediation (GGM) models which generalize models of gauge mediation. We find superpartner spectra that are markedly different from those of typical gauge and gaugino mediation scenarios. While typical gauge mediation predictions of either a neutralino or stau next-to-lightest supersymmetric particle (NLSP) are easily reproducible with the GGM parameters, chargino and sneutrino NLSPs are generic for many reasonable choices of GGM parameters.

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I. INTRODUCTION

Supersymmetry (SUSY) is one of the most well-motivated and well-studied extensions to the Standard Model (SM). If SUSY is broken at about the TeV scale, it solves the gauge hierarchy problem of the SM and also explains the existence of dark matter. One major problem with such models is the presence of flavor changing neutral currents (FCNCs); this has motivated the study of gauge mediated supersymmetry breaking (GMSB) where SUSY breaking is communicated to the observable sector through the Standard Model interactions [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Flavor violating dynamics are then available only through Yukawa interactions; any new FCNCs are aligned with the SM and are therefore small.

From the phenomenological perspective, GMSB is usually described through the introduction of heavy messenger fields. These models are characterized by two parameters: the messenger scale M , where the soft parameters are generated, and Λ the effective scale of SUSY breaking in the visible sector. Up to renormalization effects, the superpartner masses are then completely determined¹ by their Standard Model quantum numbers and Λ . Typical weakly coupled GMSB models are quite complicated, however, and require a relatively high SUSY breaking scale. It would be exciting if SUSY were broken at low energies so that messenger fields or even the hidden SUSY breaking sector would be directly observable in experiment.

For this reason, significant effort has been devoted over the years to the search for models of low energy direct gauge mediation (see for example [11, 12, 13]) or even single sector SUSY breaking [14]. It is unfortunately quite non-trivial to calculate the superpartner spectrum in the strongly interacting theories needed for implementation of direct and/or low energy gauge mediation. Indeed, it was shown in [15, 16] that usually neglected renormalization effects from a strongly interacting hidden sector may radically modify standard GMSB predictions.

Recently, Meade, Seiberg, and Shih [17] have succeeded in giving a general characterization of spectra in gauge mediated models, including strongly interacting ones. While certain GMSB features such as gravitino LSP, smallness of A -terms and certain sum rules remain unchanged, their results imply that spectra which are quite different from those of traditional GMSB can be obtained. Examples of weakly interacting models of this type were presented in [18] and further generalized in [19].²

Our goal in this paper is to begin the study of the phenomenology of the GGM scenario. These studies are likely to constrain the allowed GGM parameter space and also suggest new experimental signatures which do not arise in minimal GMSB models. In particular, we shall attempt to construct viable models with low messenger scales, which may allow us to probe the hidden sector directly.

We will begin by reviewing the general gauge mediation framework in section II. In section III, we begin the study of the phenomenology of GGM by considering models where sfermion and gaugino masses are controlled by two independent parameters, and the overall scale of the theory is the third parameter (a different slice of GGM parameter

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¹ We do not include μ and B parameters in our analysis.

² See [20, 21, 22, 23] for other related work.

space was recently studied in [21]). We then demonstrate that even our simplified subset of GGM parameters can be used to create models with new and possibly interesting phenomenology, and we qualitatively detail how these new mass hierarchies differ from previously considered models of GMSB and gaugino mediation models. We conclude by calculating the mass spectrum at certain benchmark points and showing their qualitative phenomenological differences from previously considered gauge mediated models.

II. REVIEW OF GENERAL GAUGE MEDIATION

To describe strongly interacting models of GMSB, a model independent formulation of gauge mediation is necessary. Such a formulation was proposed in [17]: the theory decouples into the MSSM and a separate SUSY breaking sector in the limit where MSSM gauge couplings tend to zero (and M_{Pl} to infinity). With these assumptions, one may relate the superpartner spectrum to one- and two-point correlation functions of the supercurrent \mathcal{J} . Current conservation $D^2\mathcal{J} = \overline{D}^2\mathcal{J} = 0$ leads to the following expressions for one- and two-point correlation functions³:

$$\begin{aligned}\langle J(x) \rangle &= \zeta \\ \langle J(p)J(-p) \rangle &= \tilde{C}_0(p^2/M^2; M/\Lambda_{UV}) \\ \langle j_\alpha(p)\bar{j}_{\dot{\alpha}}(-p) \rangle &= -\sigma_{\alpha\dot{\alpha}}^\mu p_\mu \tilde{C}_{1/2}(p^2/M^2; M/\Lambda_{UV}) \\ \langle j_\mu(p)j_\nu(p) \rangle &= -(p^2\eta_{\mu\nu} - p_\mu p_\nu)\tilde{C}_1(p^2/M^2; M/\Lambda_{UV}) \\ \langle j_\alpha(p)j_\beta(-p) \rangle &= \epsilon_{\alpha\beta}M\tilde{B}_{1/2}(p^2/M^2)\end{aligned}\tag{1}$$

where M is a characteristic scale of the theory, Λ_{UV} is a UV cutoff and a common factor of $(2\pi)^4\delta^{(4)}(0)$ is understood. The four functions \tilde{C}_0 , $\tilde{C}_{1/2}$, \tilde{C}_1 , and $\tilde{B}_{1/2}$ serve to characterize the hidden sector contribution to the current-current correlators.

When these currents carry MSSM quantum numbers, each $\tilde{C}_{j=0,1/2,1}^{(r)}$ and $\tilde{B}_{1/2}^{(r)}$ gains a new index $r = 3, 2, 1$ which labels the $SU(3) \times SU(2) \times U(1)$ gauge groups. After considering the effective action from this coupling of hidden sector correlators with the gauge supermultiplets, the gaugino and sfermion masses are given in the effective theory at scale M by

$$\begin{aligned}M_r &= g_r^2 M \tilde{B}_{1/2}^{(r)}(0) \\ m_f^2 &= g_1^2 Y_f \zeta + \sum_{r=1}^3 g_r^4 c_2(f; r) M^2 A_r,\end{aligned}\tag{2}$$

where

$$\begin{aligned}A_r &= -\int \frac{d^4p}{(2\pi)^4} \frac{1}{M^2 p^2} \left(3\tilde{C}_1^{(r)}(p^2/M^2) - 4\tilde{C}_{1/2}^{(r)}(p^2/M^2) + \tilde{C}_0^{(r)}(p^2/M^2) \right) \\ &= -\frac{1}{16\pi^2} \int dy \left(3\tilde{C}_1^{(r)}(y) - 4\tilde{C}_{1/2}^{(r)}(y) + \tilde{C}_0^{(r)}(y) \right)\end{aligned}\tag{3}$$

and $c_2(f; r)$ is the quadratic Casimir invariant of gauge group r of fermion f . Since superpartner masses in (2) are generated at the messenger scale, it is convenient to identify the scale M with the scale of messenger masses. We also note that in addition to its dependence on A_r , B_r and ζ , the superpartner spectrum at the electroweak symmetry breaking scale is modified due to renormalization group (RG) evolution between the messenger scale M and the electroweak scale.

We would now like to identify benchmark points in the parameter space of GGM. To this end we will consider GMSB models with N_5 messengers in the $\mathbf{5}$ and $\overline{\mathbf{5}}$ representations of $SU(5)$. As usual, fermionic components of messenger supermultiplets are characterized by mass M while scalar components have mass squared $M^2 \pm F$. In regular GMSB models [26],

$$\begin{aligned}M_r &= \frac{\alpha_r}{4\pi} N_5 \frac{F}{M} g(x) \\ m_f^2 &= 2N_5 \left| \frac{F}{M} \right|^2 \sum_r \left(\frac{\alpha_r}{4\pi} \right)^2 c_2(f; r) f(x),\end{aligned}\tag{4}$$

³ See [17] and [20] for more details.

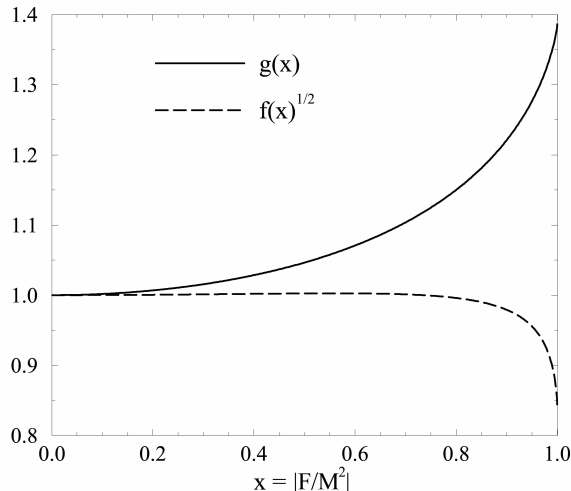


FIG. 1: The functions $g(x)$ and $\sqrt{f(x)}$ parameterizing gaugino and sfermion masses, respectively. Figure taken from [26].

where

$$\begin{aligned} g(x) &= \frac{1}{x^2} [(1+x) \log(1+x) + (1-x) \log(1-x)] \\ f(x) &= \frac{1+x}{x^2} [\log(1+x) - 2\text{Li}_2(x/[1+x]) + \frac{1}{2}\text{Li}_2(2x/[1+x])] + (x \rightarrow -x), \end{aligned} \quad (5)$$

where $x = F/M^2$.

For small x , $g(x)$ and $f(x)$ both approach 1, and we can specify points in the GGM parameter space corresponding to models of minimal GMSB:

$$\begin{aligned} B_r = B &= \frac{N_5}{16\pi^2} \left(\frac{F}{M^2} \right) \\ A_r = A &= 2 \frac{N_5}{(16\pi^2)^2} \left(\frac{F}{M^2} \right)^2 = 2 \frac{B^2}{N_5} \\ \zeta &= 0. \end{aligned} \quad (6)$$

Since soft masses are generated at one loop, it is often convenient to discuss the low energy spectrum in terms of the effective SUSY breaking scale in the visible sector, $\Lambda = F/M \sim 100$ TeV. In GGM, on the other hand, the effective scale of SUSY breaking could be smaller than 10^5 GeV since gauginos formally arise at tree level and sfermion mass squareds arise at one loop.

III. THE MINIMAL GENERAL GAUGE MEDIATION FRAMEWORK

In this paper we will study a three parameter subspace of GGM models. We will assume that $\zeta = 0$ and that values of A_r and B_r are independent of the gauge group. These models are described by a characteristic messenger scale M , an overall suppression of gaugino and sfermion masses relative to M , and the ratio between these masses.

Note that in minimal GMSB models, gaugino masses arise at 1-loop and sfermion mass squareds arise at 2-loops in the effective theory: hence, gaugino and sfermion masses naturally both have a 1-loop suppression factor and are approximately equal at the messenger scale. One can see from (4) and (5) that the ratio of gaugino and sfermion soft masses can be modified in models with $F/M^2 \sim 1$; however, this typically happens in models with a strongly interacting dynamical SUSY breaking sector and a messenger scale close to 100 TeV. While calculable examples exist in the literature [11, 12], they typically allow only $\mathcal{O}(1)$ changes in sfermion to gaugino mass ratios. In effect, there is very little freedom in GMSB models to change the ratio of sfermion mass to gaugino mass by more than an $\mathcal{O}(1)$ factor. Our three parameters allow us to explore the consequences of tuning the sfermion to gaugino mass ratio by a large factor.

An alternative approach to modifying superpartner mass ratios would involve allowing the number of messengers, N_5 , to take arbitrary values. This approach was considered in Ref. [26] by adopting messengers to be in extended

gauge messenger multiplets. Clearly, since gaugino and sfermion masses scale as N_5 and $\sqrt{N_5}$, respectively, an arbitrary mass ratio can be obtained if N_5 were allowed to be arbitrarily large. Indeed, GMSB models with extremely large values of N_5 are interesting since the superpartner spectrum in this limit is the spectrum of gaugino mediation (\tilde{g} MSB) [31, 32, 33]. Typically, only small values of $N_5 < 5$ to 10 (depending on the messenger scale) are considered in the literature in order to maintain perturbativity.

Our parametrization allows the interpolation between spectra of minimal GMSB and those of \tilde{g} MSB. In fact, it is more general than either of these two scenarios. This is due to the fact that in \tilde{g} MSB models considered so far, the compactification (messenger) scale was large; hence, as a consequence of RG evolution, at the electroweak scale sfermion masses become comparable to gaugino masses. In contrast, GGM allows the messenger scale to be as low as 10 TeV which results in a “pure” \tilde{g} MSB spectrum with sfermions significantly lighter than gauginos.

In our calculation, we will assume that the mass couplings $m_{H_1}^2$ and $m_{H_2}^2$ for both Higgs doublets are equal to the left-handed slepton soft mass squared term $m_{\tilde{L}_L}^2$ at the scale M . We set $\tan\beta = 10$ and we set the gravitino mass to be $m_{3/2} = F/(\sqrt{3}M_{\text{Pl}})$, where $F/M = 10^5$ GeV and $M_{\text{Pl}} = (8\pi G_N)^{-1/2} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck scale⁴. We then use Softsusy 2.0.17 [28] to determine the superpartner spectra. Parameter regions (which we require to have a ground state with broken electroweak symmetry) and the corresponding NLSP species are shown in Fig. (2) and Fig. (3) for different choices of the messenger scale. We also impose the current experimental lower mass bounds on NLSPs in GMSB scenarios: neutralinos at 114.0 GeV, squarks at 250.0 GeV, sleptons at 87.4 GeV, charginos at 101.0 GeV, sneutrinos at 43.7 GeV [29], and gluinos 240.0 GeV [30]. These bounds remove the gluinos and sneutrinos, but leave some of the chargino region intact, as evident by the delineated regions in Fig. (2) and Fig. (3). In addition, the points toward the right, where $\log_{10} B \rightarrow 0$, are disfavored from a theoretical perspective, since the NLSP masses at m_Z in this limit are $\mathcal{O}(10 \text{ TeV})$ and lead to a “little hierarchy” problem.

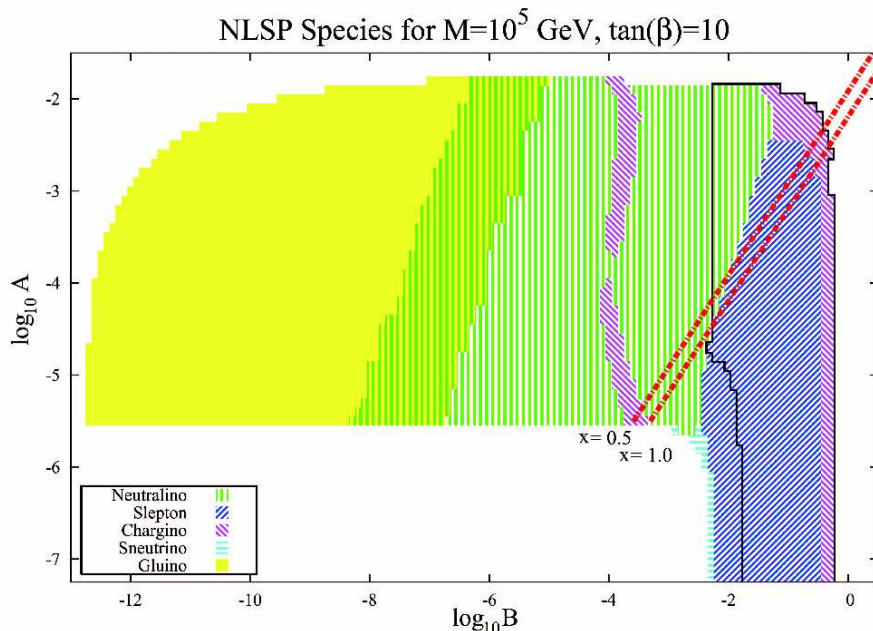


FIG. 2: (color online). NLSP regions for $M = 10^5$ GeV, $\tan\beta = 10$, in general gauge mediation. The solid outlined region satisfies constraints on NLSP mass from direct experimental searches. The dashed lines indicate the equivalent B and A relations for $x = 0.5$ and 1.0 in (6).

A. Analysis

We can compare our spectra to a benchmark GMSB scenario with $\Lambda = 10^5$ GeV, $M_{\text{mess}} = 10^5$ or 10^7 GeV, and N_5 small. The dashed line of Fig. (3) depicts models with GMSB-like parameters of $\Lambda = 10^5$ GeV, $M_{\text{mess}} = 10^7$ GeV,

⁴ We performed some scans varying $\tan\beta$ from 3 to 50 and observed qualitatively similar results.

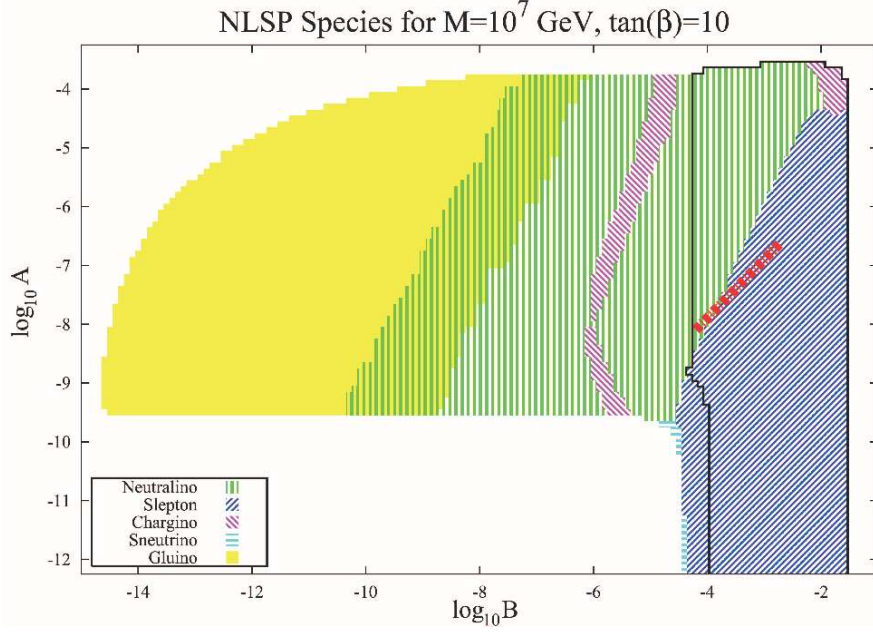


FIG. 3: (color online). Same as Fig. (2), except with $M = 10^7$ GeV. The dashed line show models equivalent to GMSB models with $\Lambda = 10^5$ GeV, $M_{\text{mess}} = 10^7$ GeV, and $N_5 = 1$ to 30.

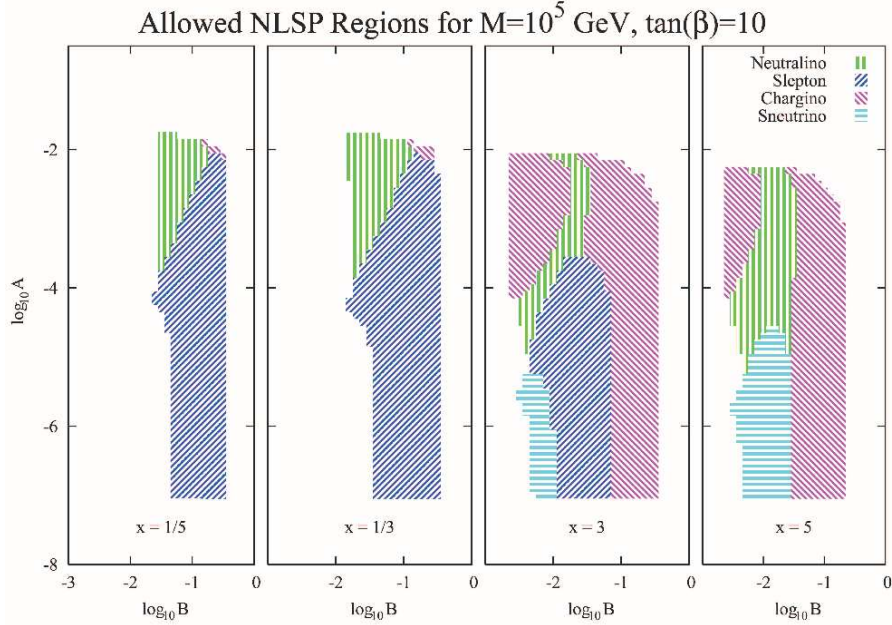
N_5 from 1 to 30, and with $m_{\tilde{f}}/m_{\tilde{g}} \simeq \mathcal{O}(1)$, since x_i is small and $g(x_i) \approx f(x_i) \approx 1$. For models that preserve gauge coupling perturbativity up to the GUT scale, N_5 is necessarily smaller. In the case of low energy SUSY breaking with $\Lambda \sim M_{\text{mess}} \sim 10^5$ GeV the ratio of corresponding GGM parameters A and B is very sensitive to the value of $x = F/M^2$ and can vary by a factor of 2. This is taken into account in Fig. (2).

There are also regions where GGM parameters lead to spectra that are markedly different than those of traditional GMSB models (Table 1). In this table we show the spectra of three GGM models (which we will refer to as GGM1, GGM2, and GGM3 respectively) and also two models of traditional gauge mediation (which we will refer to as GMSB1, GMSB2 respectively). In particular, we find that gauge mediation models do not have to obey the typical low-energy hierarchy of $m_{\tilde{\ell}_R} < m_{\tilde{\chi}_1^0} < m_{\tilde{\nu}_L} \simeq m_{\tilde{\ell}_L} < m_{\tilde{\chi}_2^0} < m_{\tilde{q}}$ for the case of a stau NLSP (cf. GMSB 1), or $m_{\tilde{\chi}_1^0} < m_{\tilde{\ell}_R} < m_{\tilde{\nu}_L} \simeq m_{\tilde{\ell}_L} < m_{\tilde{\chi}_2^0} < m_{\tilde{q}}$ in the case of a bino NLSP (cf. GMSB 2). For example, the model GGM1 has both gaugino masses and sfermion mass squareds as approximately 1-loop suppressed relative to the messenger scale $M = 10^5$ GeV, and leads to a SUSY spectrum with all gauginos lighter than all scalars. Model GGM2, on the other hand, has gaugino masses approximately $1/(128\pi^3)$ suppressed, while the sfermions start nearly massless, and all sleptons stay lighter than all gauginos after RG evolution. Clearly, the phenomenology of such situations would be radically different from traditional GMSB scenarios. In the case of GGM1, squark production is heavily suppressed at the LHC from kinematics and the parton momenta fraction, and hence SUSY production is dominated by gluino pair production. The allowed modes for gluino decay are then a three-body final state of $q + q + \tilde{\chi}_i^0$ with 2 hard jets and missing energy (and a likely Z from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0$ decay) or a two-body decay of $\tilde{g} \rightarrow g + G$. On the other hand, for GGM2, long cascade decay chains with lots of leptons are possible. These simple examples demonstrate two notably distinct sets of signals, both originating from the general gauge mediation framework. We also present model GGM3, which sets both gaugino and sfermion masses to be nearly tree-level in the theory, and because of a large cancelation in the diagonalization of the gaugino mixing matrices, the NLSP is a chargino.

As pointed out in [17] another interesting feature of GGM parameter space is that it interpolates between the phenomenology of GMSB and \tilde{g} MSB models. In fact, GGM admits even more general phenomenology. Indeed, while existing models of \tilde{g} MSB [31, 33] have a large hierarchy between sfermion and gaugino masses at the compactification scale (usually taken to be close to the GUT scale), this hierarchy is washed out at the TeV scale due to the effects of long RG evolution. As expected, GGM easily reproduces the spectra of such models. On the other hand, the bottom-up approach of GGM allows one to take an effective messenger scale to be as low as 10^4 GeV leading to a “pure \tilde{g} MSB” spectrum at the electroweak scale with the 4π suppression factor between sfermion and gaugino masses intact. The differences between low-scale and high-scale \tilde{g} MSB are highlighted by a few representative spectra in Table 2. We note that because of the relatively small running scale, low-scale \tilde{g} MSB models, like GGM4 and GGM5, characteristically have slepton NLSPs, and hence a low-scale \tilde{g} MSB model with a bino NLSP is disfavored.

TABLE I: Comparison of Minimal General Gauge Mediation and Minimal GMSB

		GGM1	GGM2	GGM3		mGMSB1	mGMSB2
inputs:	M	10^5	10^7	10^4	M_{mess}	10^5	10^7
	$\log_{10} B$	-2.1	-3.6	-0.4	Λ	10^5	10^5
	$\log_{10} A$	-2.25	-10	-1.5	N_5	3	1
	$\tan \beta$	10	10	10		10	10
	c_{grav}	1.0	1.0	1.0		1.0	1.0
	$\text{sign}(\mu)$	+	+	+		+	+
neutralinos:	$m_{\chi_1^0}$	174	533	137		547	132
	$m_{\chi_2^0}$	353	742	144		611	256
	$m_{\chi_3^0}$	1310	753	865		625	511
	$m_{\chi_4^0}$	1320	1030	1620		1080	522
charginos:	$m_{\chi_1^\pm}$	345	736	128		603	258
	$m_{\chi_2^\pm}$	1310	1030	1630		1080	519
Higgs:	m_{h^0}	123	116	116		116	112
	m_{H^0}	3050	849	735		833	619
	m_{A^0}	3050	849	734		833	619
	m_{H^\pm}	3050	853	739		837	624
sleptons:	$m_{\tilde{\tau}_R}$	1390	174	348		276	191
	$m_{\tilde{e}_R}$	1400	179	349		279	195
	$m_{\tilde{\ell}_L}$	2770	417	728		578	372
	$m_{\tilde{\nu}_L}$	2780	410	727		574	363
squarks:	$m_{\tilde{t}_1}$	7620	1620	2360		1860	875
	$m_{\tilde{t}_2}$	8260	1770	2500		2000	1010
	$m_{\tilde{u}_L}$	8390	1800	2510		2040	1050
	$m_{\tilde{u}_R}$	8070	1780	2440		1990	1010
	$m_{\tilde{d}_L}$	8430	1810	2520		1970	1060
	$m_{\tilde{d}_R}$	8030	1760	2430		2050	1000
gluino:	M_3	1060	2630	4020		2740	804

FIG. 4: (color online). Allowed NLSP regions for $M = 10^5$ GeV, $\tan \beta = 10$, in general gauge mediation. Here, we set $A_1 = x A_2 = x A_3 = x A$, and similarly for B , to use in (2).

A notable feature evident in our GGM parameter plots is the intersection of three discrete NLSP regions: neutralino (bino), chargino (wino), and slepton (stau) NLSPs. This triple point region likely leads to very interesting phenomenology and new collider signals, since all three particles are highly degenerate in this parameter space. In

TABLE II: Gaugino mediation hierarchy comparison. The \tilde{g} MSB hierarchies are taken from [31]. LEP constraints rule out these models, but we present them for comparison.

		GGM4	GGM5	GGM6		\tilde{g} MSB1	\tilde{g} MSB2	\tilde{g} MSB3
inputs:	M	10^4	10^5	2×10^{16}	$m_{1/2}$	200	400	400
	$\log_{10} B$	-1.0	-2.4	-13.4	$m_{H_u}^2$	$(200)^2$	$(400)^2$	$(400)^2$
	$\log_{10} A$	-3.0	-4.6	-29	$m_{H_d}^2$	$(300)^2$	$(600)^2$	$(400)^2$
	$\tan \beta$	10	10	10	μ	370	755	725
					B	315	635	510
					y_t	0.8	0.8	0.8
neutralinos:	$m_{\chi_1^0}$	141	79	164		78	165	165
	$m_{\chi_2^0}$	172	144	308		140	315	315
	$m_{\chi_3^0}$	229	263	523		320	650	630
	$m_{\chi_4^0}$	430	291	537		360	670	650
charginos:	$m_{\chi_1^\pm}$	158	143	311		140	315	315
	$m_{\chi_2^\pm}$	429	289	533		350	670	645
Higgs:					$\tan \beta$	2.5	2.5	2.5
	m_{h^0}	106	107	113		90	100	100
	m_{H^0}	220	315	579		490	995	860
	m_{A^0}	219	314	578		490	1000	860
	m_{H^\pm}	183	324	584		495	1000	860
sleptons:	$m_{\tilde{e}_R}$	82	103	155		105	200	160
	$m_{\tilde{e}_L}$	163	206	281		140	275	285
	$m_{\tilde{\nu}_L}$	143	189	269		125	265	280
stops:	$m_{\tilde{t}_1}$	616	600	653		350	685	690
	$m_{\tilde{t}_2}$	681	673	846		470	875	875
other squarks:	$m_{\tilde{u}_L}$	657	666	856		470	945	945
	$m_{\tilde{u}_R}$	649	649	832		450	905	910
	$m_{\tilde{d}_L}$	665	674	862		475	950	945
	$m_{\tilde{d}_R}$	646	647	824		455	910	905
gluino:	M_3	1135	536	938		520	1000	1050

principle, there could also be other combinations of NLSPs that give triple point phenomenology. (For example, there is a triple point of sneutrinos, neutralinos, and charginos in the rightmost plot of Fig. (4).) One immediate consequence of highly degenerate NLSPs, however, is that the typical dark matter relic density calculation must now include coannihilations, and so a full analysis of triple point phenomenology must first determine what the favored degenerate mass range is in order to give an appropriate dark matter relic density. We leave a full analysis of triple point phenomenology for future work.

B. Extensions of minimal set of parameters

We now study how simple extensions of minimal set of parameters considered so far affect our results by allowing the variation of A_1 and B_1 relative to the other A and B parameters. Specifically, we set $A_1 = xA_2 = xA_3 \equiv xA$ and $B_1 = xB_2 = xB_3 \equiv xB$, where $x = 1/5, 1/3, 3$, and 5 .

As can be seen in Fig. (4), this leads to interesting phenomenological consequences. In particular, note that for $x > 1$ the charged slepton NLSP is not a generic prediction of gauge mediation. Instead, for a large set of parameters, sneutrinos and charginos become the NLSP. This is especially interesting in view of the fact that the $x > 1$ region of GGM parameter space squeezes the superpartner spectrum and thus alleviates the little hierarchy problem.

On a separate note, in Fig. (2) and Fig. (3), there are new regions where gluino NLSPs are present. (In Fig. (2), with $\log_{10} B$ between -10 and -6 , the gluino region overlaps with the neutralinos; similarly for Fig. (3).) The entire gluino region has masses calculated at best to be $\mathcal{O}(0.1 \text{ GeV})$, and therefore ruled out; yet it should be possible to construct GGM models with viable gluino NLSPs by adjusting the parameters $A_r, \tilde{B}_{1/2}^{(r)}$ appropriately.

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